第八届强子谱和强子结构研讨会@广西师范大学

Probing DK interaction in B decays and heavy-ion collisions

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Based on: Phys. Rev. D **109** (2024) 056014
ArXiv: 2506.23476

2025-7-14

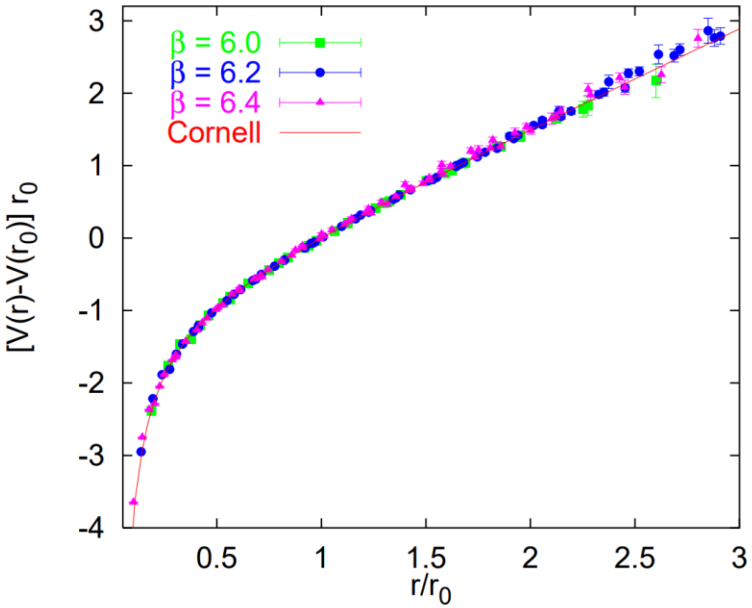
Outline

- Exotic states and hadron-hadron interactions
- Study the DK interaction in B decays
- Study the DK interaction in heavy-ion collisions
- Summary and Outlook

Strong interaction and hadron structure

➢ **Cornell model** $V_0(r) = -\frac{4\alpha_s}{3r} + \sigma r$

E. Eichten et al., Phys. Rev. Lett. 34 (1975) 369-372



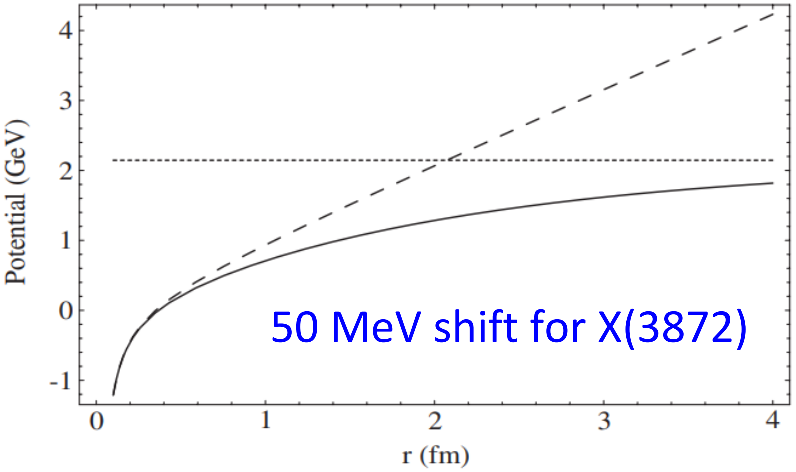
Gunnar S. Bali, Phys. Rept. 343 (2001) 1-136

➢ **Godfrey-Isgur model**

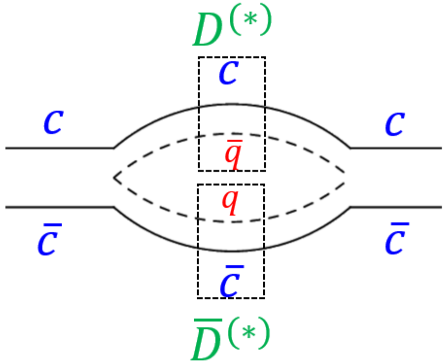
- Spin-Spin Term
- Spin-Orbit Term
- Tensor Term

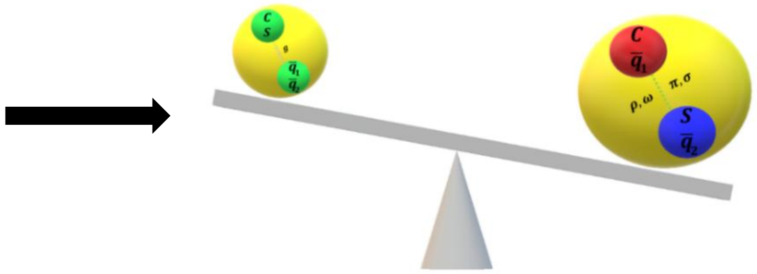
S. Godfrey et al., Phys. Rev. D32 (1985) 189-231

➢ **Screen potential** $br \to V^{\mathrm{scr}}(r) = \frac{b(1-e^{-\mu r})}{\mu}$



Bai-Qing Li, et al., Phys. Rev. D 79 (2009) 094004

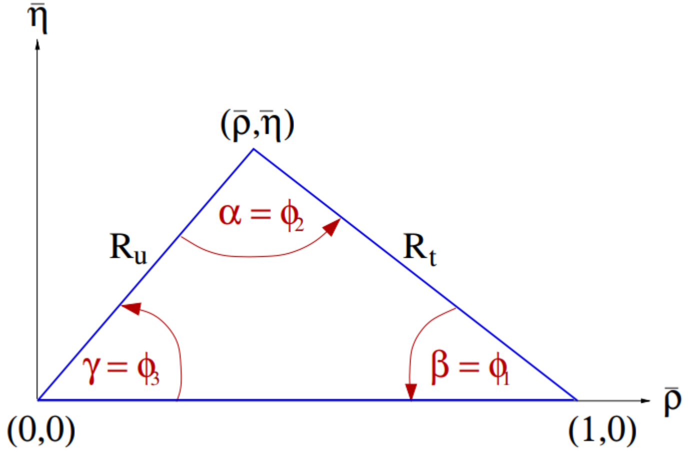


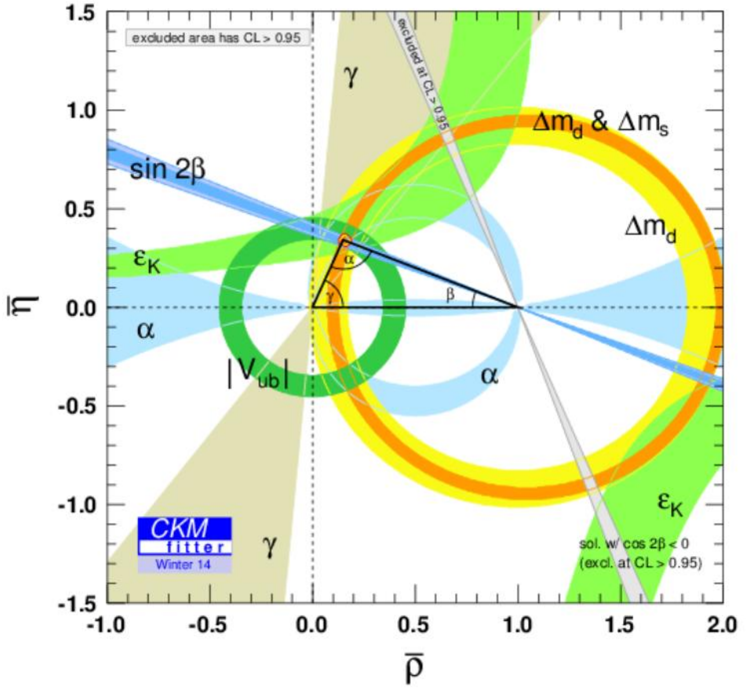


The complex non-perturbative dynamics of QCD give rise to diverse structural formations in hadronic matter

Heavy flavor Physics

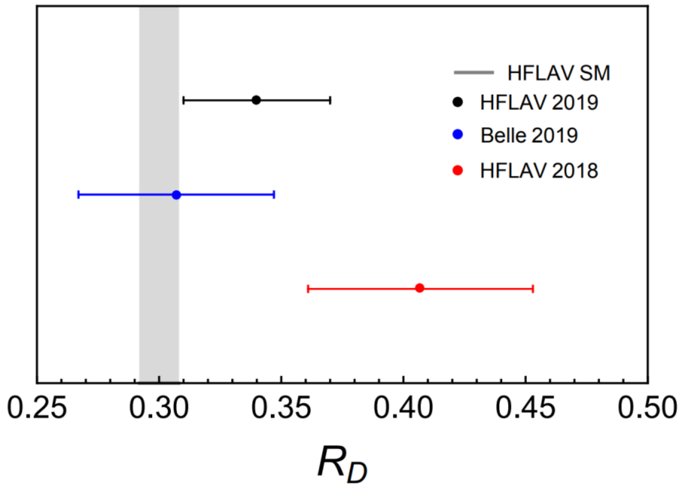
- **Precise test for Standard Model**

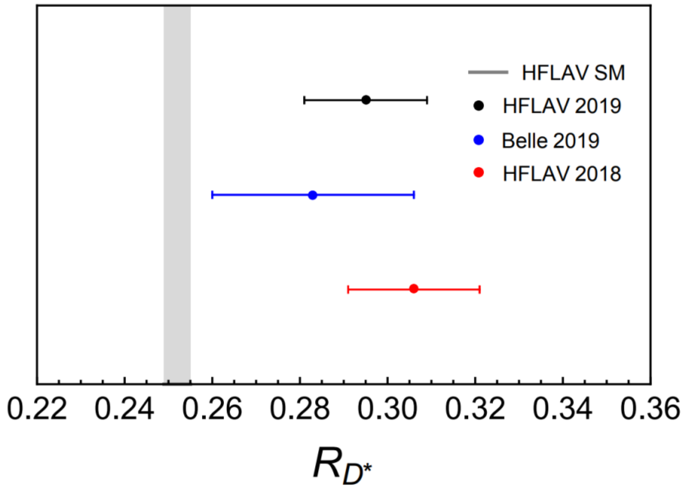




- **Search for New Physics**

$$R^{SM}_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\bar{\nu})}{\Gamma(B \to D^{(*)}\ell\bar{\nu})}, \qquad (\ell = \mu, e)$$





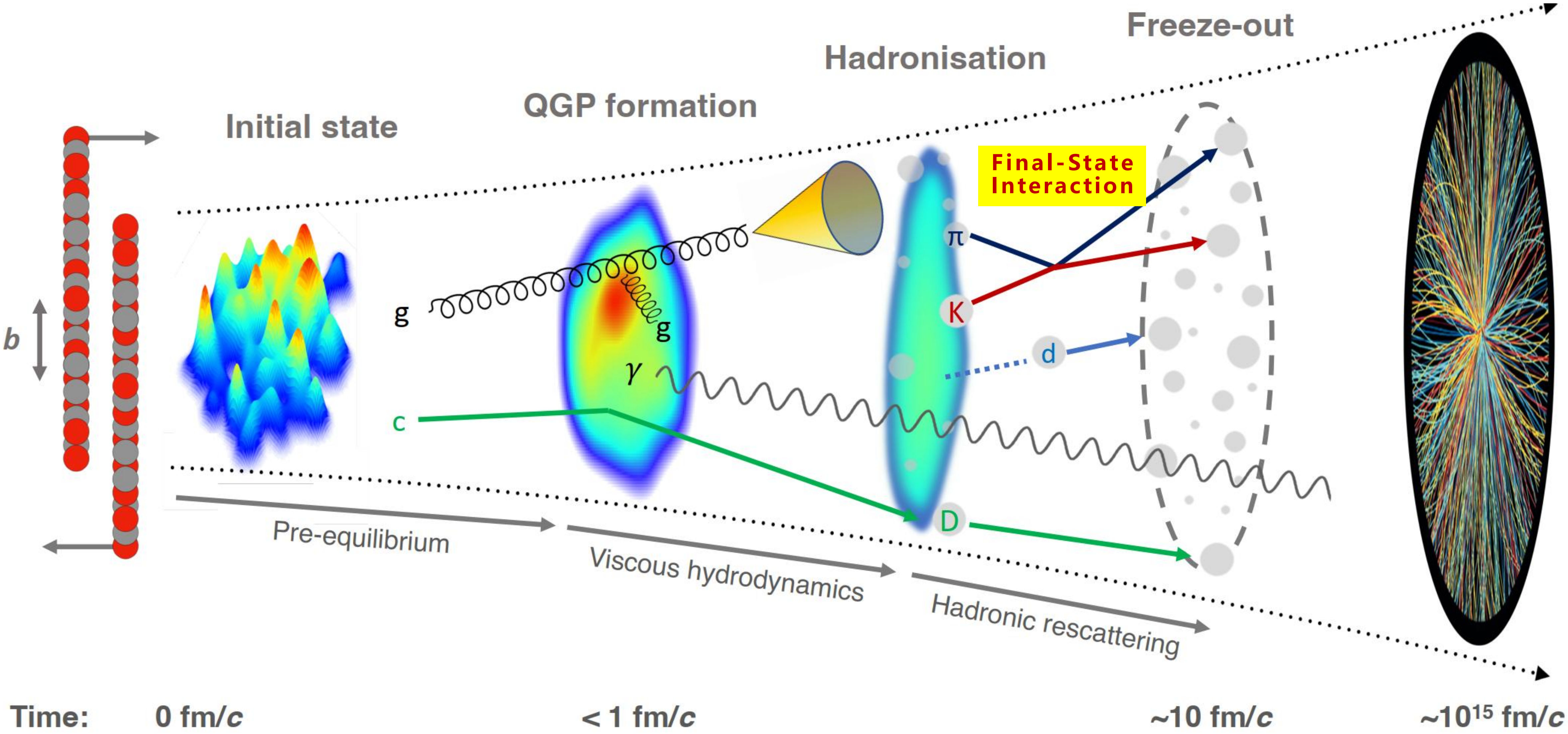
Productions of exotic states in b-flavored hadron decays

- **A lot of exotic states were discovered in b-flavored hadron decays**

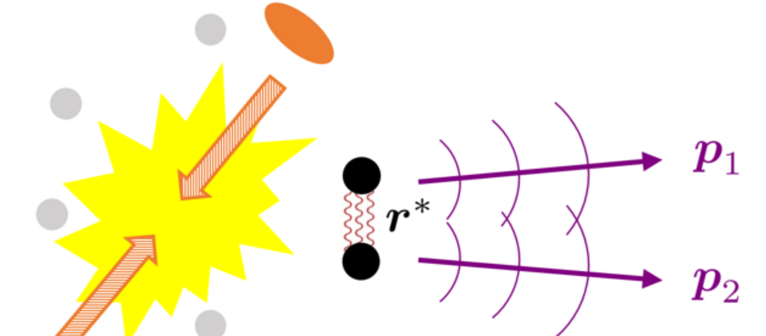
Decay modes	New states	Decay modes	New states
$\Xi_b \to J/\psi \Lambda K$	$P_{cs}(4459)$	$\Lambda_b \to J/\psi p K$	$P_c(4312)/P_c(4440)/P_c(4457)$
$\Lambda_b \to D p \pi$	$\Lambda_c(2940)$	$B^+ \to D_s{}^+ \pi^0 \bar{D}^0$	$D_{s0}(2317)$
$B_s \to J/\psi p \bar{p}$	$P_c(4337)$	$B^+ \to D_s{}^{*+} \pi^0 \bar{D}^0$	$D_{s1}(2460)$
$B \to J/\psi \Lambda \bar{p}$	$P_{cs}(4338)$	$B^+ \to D^- K^+ D^+$	$X_0(2900)/X_1(2900)$
$B^+ \to D_s{}^+ \pi^+ D^-$	$T_{c\bar{s}0}(2900)^{++}$	$B^+ \to J/\psi \phi K^+$	$X(4140)/X(4274)$
$B^0 \to D_s{}^+ \pi^- \bar{D}^0$	$T_{c\bar{s}0}(2900)^0$	$B^+ \to J/\psi \phi K^+$	$X(4500)/X(4700)$
$B^+ \to D^0 \bar{D}^{*0} K^+$	$X(3872)$	$B^+ \to J/\psi K^+ \phi$	$Z_{cs}(4000)/Z_{cs}(4220)$
$B^+ \to D_s{}^+ D_s{}^- K^+$	$X(3960)$	$B^0 \to \psi' \pi^\mp K^\pm$	$Z_c(4430)$
$B^+ \to J/\psi \omega K^+$	$X(3915)$	$B^0 \to \chi_{c1} \pi^\mp K^\pm$	$Z_c(4051)/Z_c(4248)$
$B^+ \to K^+ K^- K^+$	$f_0(980)$	$B^0 \to J/\psi \pi^\mp K^\pm$	$Z_c(4200)$
$B^+ \to \pi^0 \pi^0 K^+$	$f_0(980)$		

- **Providing rich physical observables to study the exotic states**
  - **Branching fraction**
  - **Invariant mass distribution**
  - **CP violation**
  - **Angular distributions**

Dynamic evolution of heavy-ion collisions



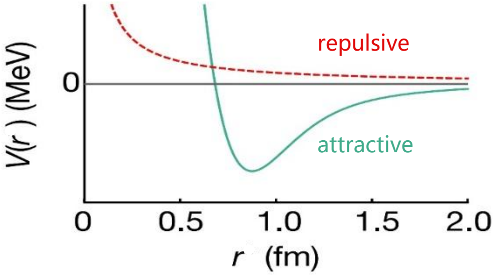
➢ Momentum correlation function



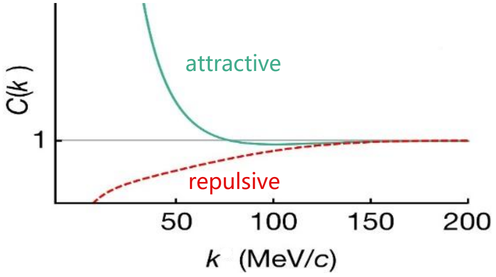
$k^* = (m_2 p_1 - m_1 p_2)/(m_1 + m_2)$

Emission source $S_{12}(r^*)$ Two-particle wavefunction $\psi(k^*, r^*)$

Interacting potential



Correlation function



↓

Schrödinger equation

↓

Two-particle wavefunction $\psi(k\ ,r\ )$

Theo. description

Koonin–Pratt formula

$$C(k) = \int S_{12}(\boldsymbol{r})\ |\psi(\boldsymbol{k}, \boldsymbol{r})|^2\ \mathrm{d}\boldsymbol{r}$$

spacial structure

final-state interactions

quantum statistics effects

Basic Properties

$C(k)$
- >1 if the interaction is **attractive**
- =1 if there is **no interaction**
- <1 if the interaction is **repulsive**

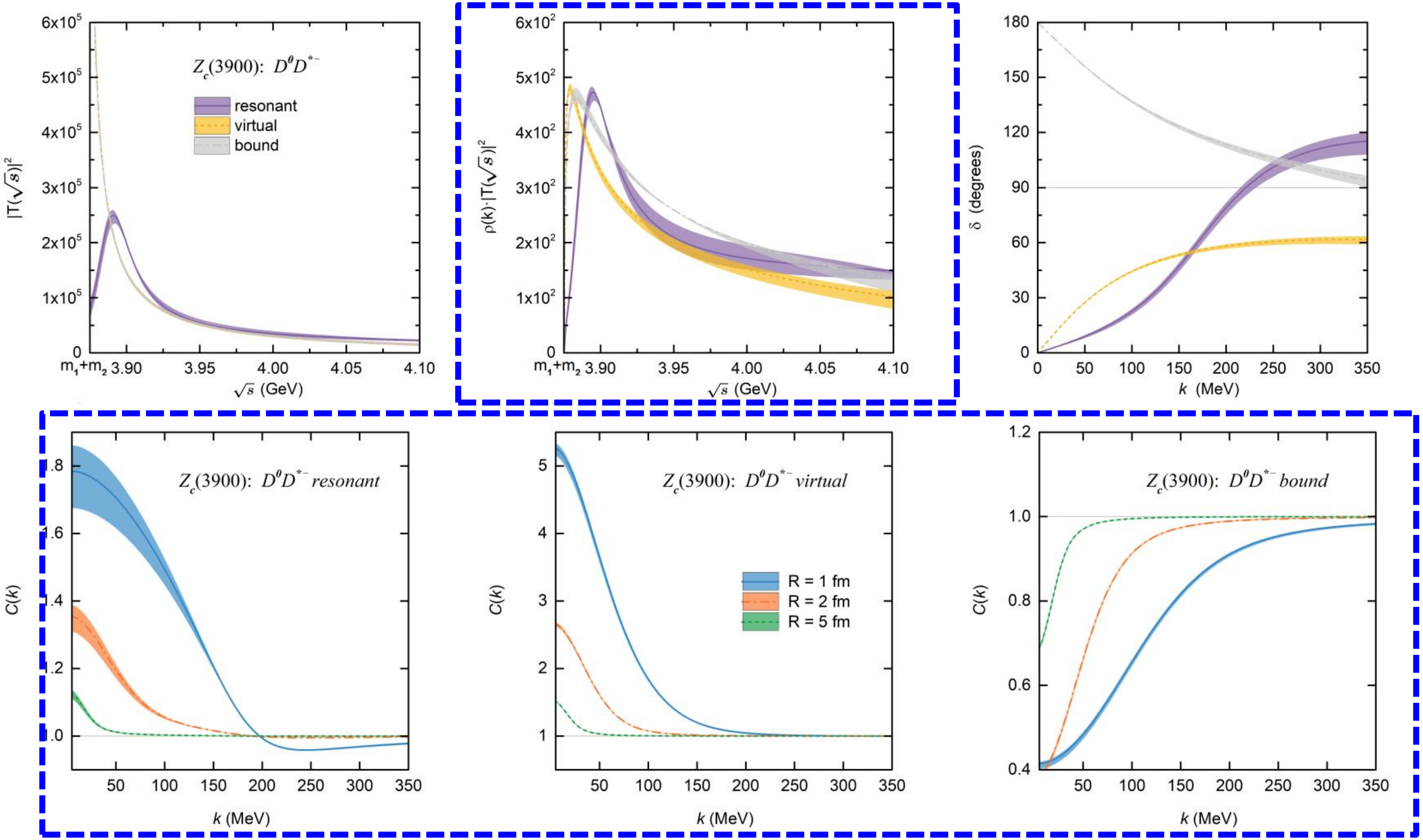
Correlation functions determine pole positions

Amplitude square

Invariant mass distribution

Phase shift

Correlation functions



Zhi-Wei Liu, et al., arXiv:2404.18607

Exotic state $D_{s0}^*(2317)$

➢ Experimental measurements of $D_{s0}^*(2317)$

$e^+e^- \to D_s^+\pi^0 X$ (BABAR, CESR CLEO) — 2003

$e^+e^- \to D_s^{*+}(D_{s0}^{*-} \to D_s^-\pi^0)$ (BESIII) — 2017

Inclusive process

2003 → 2017

Exclusive process

$B \to D_{s0}^*(\to D_s^+\pi^0)\bar{D}$ (BELLE) — 2003

- **Mass and width**

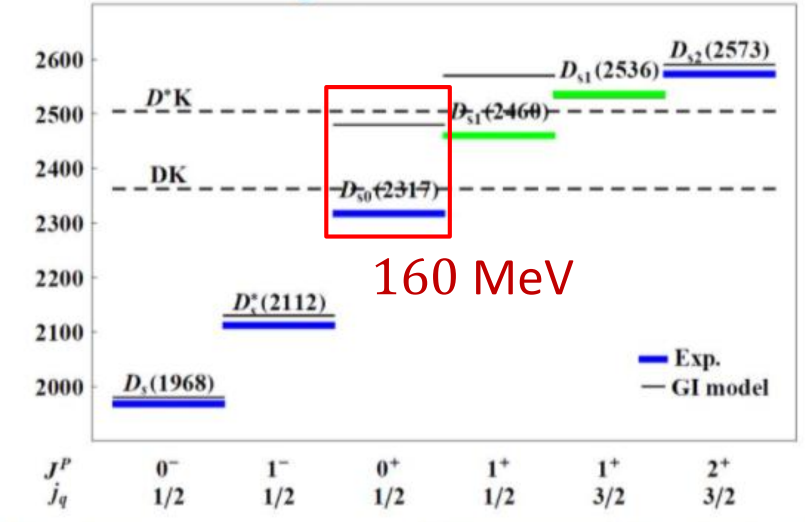
$$D_{s0}^*(2317) = 2317.8 \pm 0.5 + \frac{i}{2} < 3.8$$

- **Decay Channel**

$$D_{s0}^{*-} \to D_s^-\pi^0$$

➢ Large mass deviation

D_s spectrum



➢ Branching fraction

$$Br(D_{s0}^{*-} \to D_s^-\pi^0) \approx 1$$

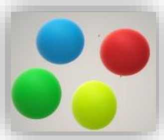
BESIII Collaboration, , Phys. Rev. D 97, 051103 (2018)

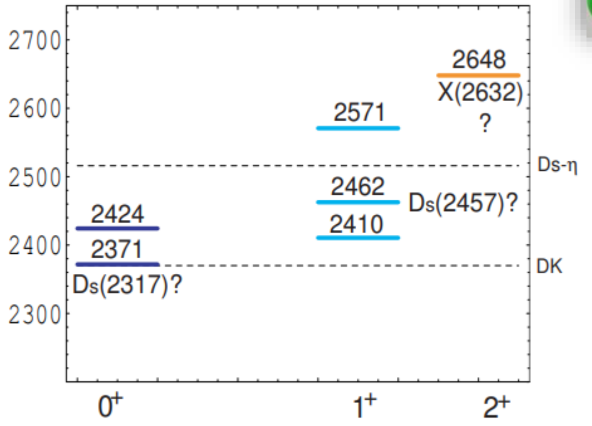
Disfavor the $D_{s0}^*(2317)$ as excited $\bar{c}s$ state

$D_{s0}^*(2317)$ is regarded as an exotic state!

Molecular interpretation of $D_{s0}^{*}(2317)$

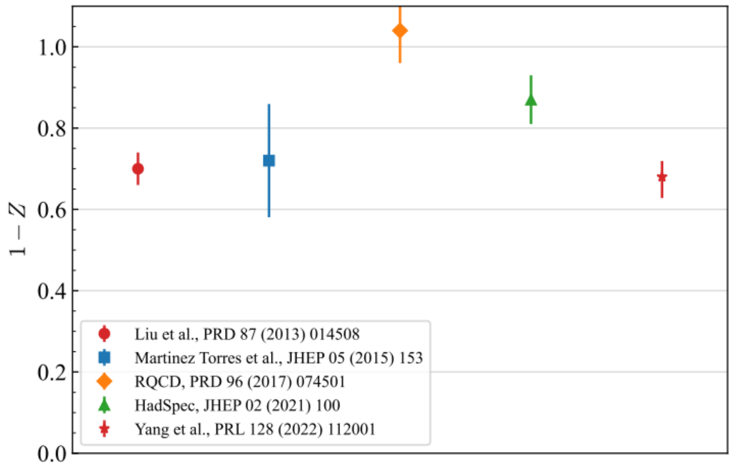
- **Compact tetraquark**





Maiani et al., Phys.Rev.D 71 (2005) 014028

- **Mixture of molecular and other component**



Guo, PoS LATTICE2022 (2023) 232

- **Molecular interpretation**

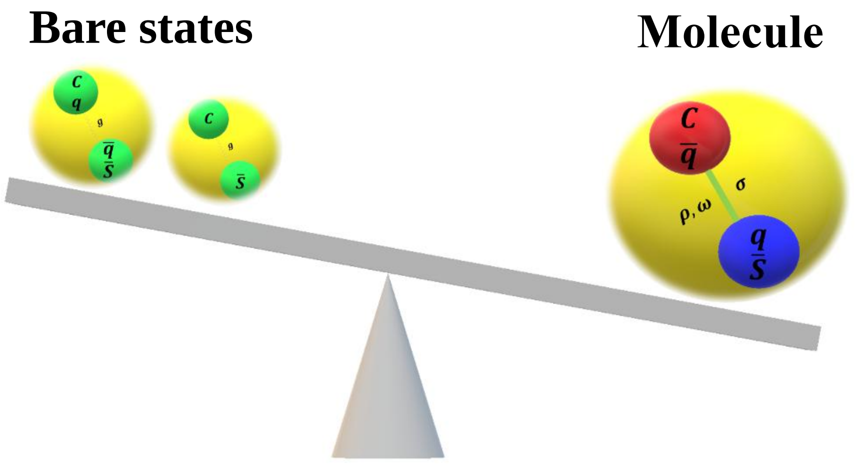
✓ **Mass and mass splitting**

$D_{s0}(2317)$	$I(J^P) = 0(0^+)$	DK
$D_{s1}(2460)$	$I(J^P) = 0(1^+)$	D^*K

ChPT Guo et al., Phys.Lett.B 641 (2006) 278-285

Lattice QCD Liu et al., Phys.Rev.D 87 (2013) 014508

✓ **Branching fraction** $Br(D_{s0}^{*-} \to D_s^- \pi^0) \approx 1$



✓ **Molecular component more than 70%**

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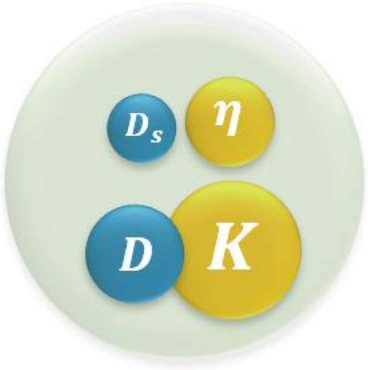
Productions of $D_{s0}^*(2317)$ in B decays

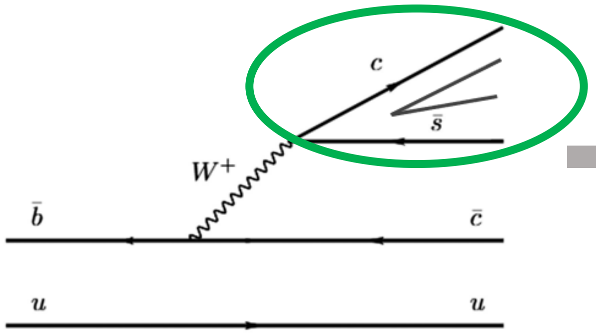
- **Explain these branching fractions**

Decay modes	PDG 10^{-3}	BarBar 10^{-3}
$B^+ \to \bar{D}^0 D_{s0}^{*+}(2317)$	$0.80^{+0.16}_{-0.13}$	$1.0 \pm 0.3 \pm 0.1$
$B^0 \to D^- D_{s0}^{*+}(2317)$	$1.06^{+0.16}_{-0.16}$	$1.8 \pm 0.4 \pm 0.3$
$B^+ \to \bar{D}^{*0} D_{s0}^{*+}(2317)$	$0.90^{+0.70}_{-0.70}$	$0.9 \pm 0.6 \pm 0.2$
$B^0 \to D^{*-} D_{s0}^{*+}(2317)$	$1.50^{+0.60}_{-0.60}$	$1.5 \pm 0.4 \pm 0.2$

$D_{s0}^*(2317)$ →



Productions of *DK* molecule in B decays



$$\mathcal{A}\left(B^- \to D_{s0}^{*-}\bar{D}^{(*)0}\right) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} a_1 \left\langle D_{s0}^{*-}|(s\bar{c})|0\right\rangle \left\langle \bar{D}^{(*)0}|(c\bar{b})|B^-\right\rangle$$

- **Form factors**

$$\langle \bar{D}^{*0}|(c\bar{b})|B^+\rangle = \epsilon_\alpha^* \left\{ -g^{\mu\alpha}(m_{\bar{D}^{*0}} + m_{B^+}) A_1(q^2) + P^\mu P^\alpha \frac{A_2(q^2)}{m_{\bar{D}^{*0}} + m_{B^+}} + i\varepsilon^{\mu\alpha\beta\gamma} P_\beta q_\gamma \frac{V(q^2)}{m_{\bar{D}^{*0}} + m_{B^+}} + q^\mu P^\alpha \left[\frac{m_{\bar{D}^{*0}} + m_{B^+}}{q^2} A_1(q^2) - \frac{m_{B^+} - m_{\bar{D}^{*0}}}{q^2} A_2(q^2) - \frac{2m_{\bar{D}^{*0}}}{q^2} A_0(q^2) \right] \right\}$$

$$\langle \bar{D}^0|(c\bar{b})|B^+\rangle = \left[P^\mu - \frac{m_{B^+}^2 - m_{\bar{D}^0}^2}{q^2} q_\mu \right] F_1(q^2) + \frac{m_{B^+}^2 - m_{\bar{D}^0}^2}{q^2} q_\mu F_0(q^2)$$

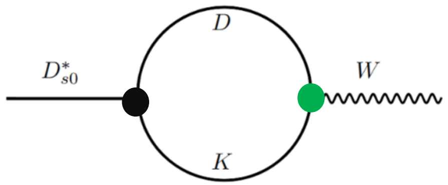
- **Decay constants**

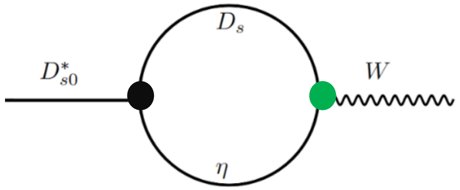
$$\langle D_{s0}^{*+}|(s\bar{c})|0\rangle = f_{D_{s0}^{*+}} p^\mu_{D_{s0}^{*+}}$$

Decay constants characterize the internal structure of exotic state

Calculating decay constant of $D_{s0}^*(2317)$

- **Effective Lagrangian approach**





$$\mathcal{L}_{D_{s0}^* DK} = g_{D_{s0}^* DK} D_{s0}^* DK, \quad \mathcal{L}_{D_{s0}^* D_s\eta} = g_{D_{s0}^* D_s\eta} D_{s0}^* D_s\eta$$

$$\mathcal{L}_{VDK} = f_1^{DK}(0) V^\mu (D\partial_\mu K - \partial_\mu D K), \quad \mathcal{L}_{VD_s\eta} = f_1^{D_s\eta}(0) V^\mu (D_s\partial_\mu \eta - \partial_\mu D_s \eta)$$

- **Loop integral**

$$\mathcal{A}_a = g_{D_{s0}^* DK} f_1^{DK}(0) \int \frac{d^4q}{(2\pi)^4} \frac{1}{k_1^2 - m_1^2} \frac{1}{k_2^2 - m_2^2} (k_1^\mu - k_2^\mu) \varepsilon_\mu(V),$$

$$\mathcal{A}_b = g_{D_{s0}^* D_s\eta} f_1^{D_s\eta}(0) \int \frac{d^4q}{(2\pi)^4} \frac{1}{k_1^2 - m_1^2} \frac{1}{k_2^2 - m_2^2} (k_1^\mu - k_2^\mu) \varepsilon_\mu(V),$$

$$\langle D_{s0}^{*+} | (s\bar{c}) | 0 \rangle = f_{D_{s0}^{*+}} p^\mu_{D_{s0}^{*+}}$$

Extracting decay constant

$$f_{D_{s0}^*}^{m_1 m_2} = g_{D_{s0}^* m_1 m_2} f_1^{m_1 m_2}(0) \frac{1}{16\pi^2} \int_0^1 dx (2x-1) ln \frac{\Delta^2}{\mu^2}$$

- **Unknown parameters**

Renormalization energy scale

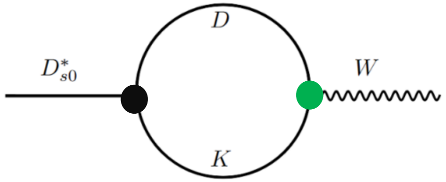
Dimensional Regularization Scheme

$$\int \frac{d^4 k_1}{(2\pi)^4} \frac{k_1^\mu - k_2^\mu}{(k_1^2 - m_1^2)[(p-k_1)^2 - m_2^2]} = \frac{p^\mu}{16\pi^2} \int_0^1 dx (2x-1) ln \frac{\Delta^2}{\mu^2}$$

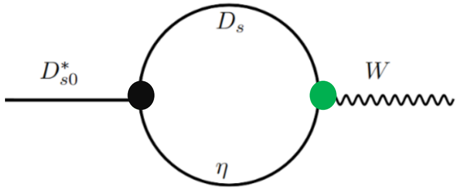
Coupling constants

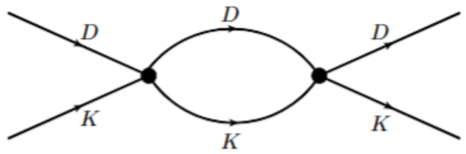
Calculating decay constant of $D_{s0}^*(2317)$

➢ Coupling constants



decay modes	Exp [34]	decay modes	Exp [34]
$D^+ \to \bar{K}^0 e^+ \nu_e$	8.72 ± 0.09	$D_s^+ \to \eta e^+ \nu_e$	2.32 ± 0.08





$$\left\langle \vec{k}' \left| T \right| \vec{k} \right\rangle = \left\langle \vec{k}' \left| T \right| \vec{k} \right\rangle + \int \frac{d^3\vec{q}}{(2\pi)^3} \left\langle \vec{k}' \left| V \right| \vec{q} \right\rangle G(s) \left\langle \vec{q} \left| T \right| \vec{k} \right\rangle$$

$$V_{DK-D_s\eta}^{J^P=0^+} = \begin{pmatrix} -2C_a & \sqrt{3}C_a \\ \sqrt{3}C_a & 0 \end{pmatrix}$$

$$G(\sqrt{s})^{D_{s0}^*} = \frac{1}{16\pi^2}\int_0^1 dx ln\frac{\Delta^2}{\mu^2}$$

$$g_i g_j = \lim_{\sqrt{s}\to\sqrt{s_0}} (\sqrt{s} - \sqrt{s_0})\, T_{ij}(\sqrt{s})$$

$$f_{D_{s0}^*}^{m_1 m_2} = g_{D_{s0}^* m_1 m_2} f_1^{m_1 m_2}(0) \frac{1}{16\pi^2}\int_0^1 dx(2x-1) ln\frac{\Delta^2}{\mu^2}$$

Similar regularization approach

Calculating the decay constant of $D_{s0}^*(2317)$

- **Strong decay constants of $D_{s0}^*(2317)$**

Couplings	$\mu = 1.00$	$\mu = 1.50$	$\mu = 2.00$
$g_{D_{s0}^* DK}$	11.75	11.92	11.95
$g_{D_{s0}^* D_s \eta}$	8.13	7.47	7.32

- **Decay constant of $D_{s0}^*(2317)$**

Decay Constants	$\mu = 1000$	$\mu = 1500$	$\mu = 2000$
$f_{D_{s0}^*(2317)}$	59.36	58.74	58.59

Decay constant of $D_{s0}^*(2317)$ is almost independent on the renormalization energy scale

Production rates of $D_{s0}^*(2317)$ in b-flavored hadron decays

- **Decay constants of $D_{s0}^*(2317)$ as the bare state**

10^{-3}

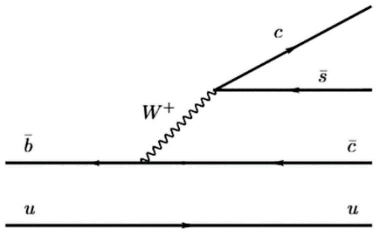
Decay modes	Ours	Experiments [29]
$B^+ \to \bar{D}^0 D_{s0}^{*+}(2317)$	0.48	$0.80^{+0.16}_{-0.13}$
$B^+ \to \bar{D}^{*0} D_{s0}^{*+}(2317)$	0.39	$0.90^{+0.70}_{-0.70}$

70%

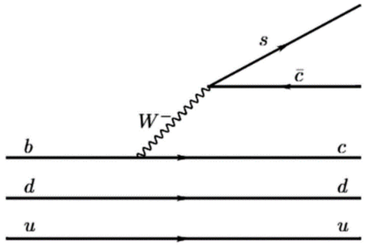
$f_{D_{s0}^*(2317)} = 59$ MeV Hadronic molecule

$f_{D_{s0}^*(2317)} = 116$ MeV Bare state

- **Production rates of $D_{s0}^*(2317)$ in b-flavored decays**



Decay modes	10^{-3} Ours
$B_s^0 \to D_s^- D_{s0}^{*+}(2317)$	0.47
$B_s^0 \to D_s^{*-} D_{s0}^{*+}(2317)$	0.27



10^{-3}

Decay modes	Branching fractions
$\Lambda_b \to \Lambda_c D_{s0}^*(2317)$	0.70
$\Xi_b \to \Xi_c D_{s0}^*(2317)$	0.58

$\mathcal{B}(\Xi_b \to \Xi_c M)/\mathcal{B}(B_s \to D_s M) \approx 1.23$

$\mathcal{B}(\Lambda_b \to \Lambda_c M)/\mathcal{B}(B \to D M) \approx 1.46$

Production rates of D_{s0}^* in heavy baryons are larger than those in heavy mesons

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Introducing a bare component in $D_{s0}^*(2317)$

➢ Contact-range EFT potential

$D_{s0}^*(2317)$

Introducing a bare state →

$$V = \begin{pmatrix} C_a + \frac{\alpha}{\sqrt{s} - m_{bare}} & -\frac{\sqrt{3}}{2} C_a \\ -\frac{\sqrt{3}}{2} C_a & 0 \end{pmatrix}$$

Mass

Compositeness

- Single-channel DK
- Single-channel DK + bare state c$\bar{s}$
- Couple-channel $DK + D_s\eta$
- Couple-channel $DK + D_s\eta$ + bare state c$\bar{s}$

More DK physical observables

➢ Scattering length and correlation function

$$T(\sqrt{s}) = \frac{V(s)}{1 - V(s) \cdot G(\sqrt{s})}$$

Scattering length →

$$-\frac{1}{a} = -8\pi\sqrt{s}T^{-1}|_{s=s_{\mathrm{th}}}$$

$$r_0 = \frac{\partial}{\partial k^2} 2(-8\pi\sqrt{s}T^{-1} + ik)$$
$$= \frac{\sqrt{s}}{\mu}\frac{\partial}{\partial s} 2(-8\pi\sqrt{s}T^{-1} + ik)\Big|_{s=s_{\mathrm{th}}}$$

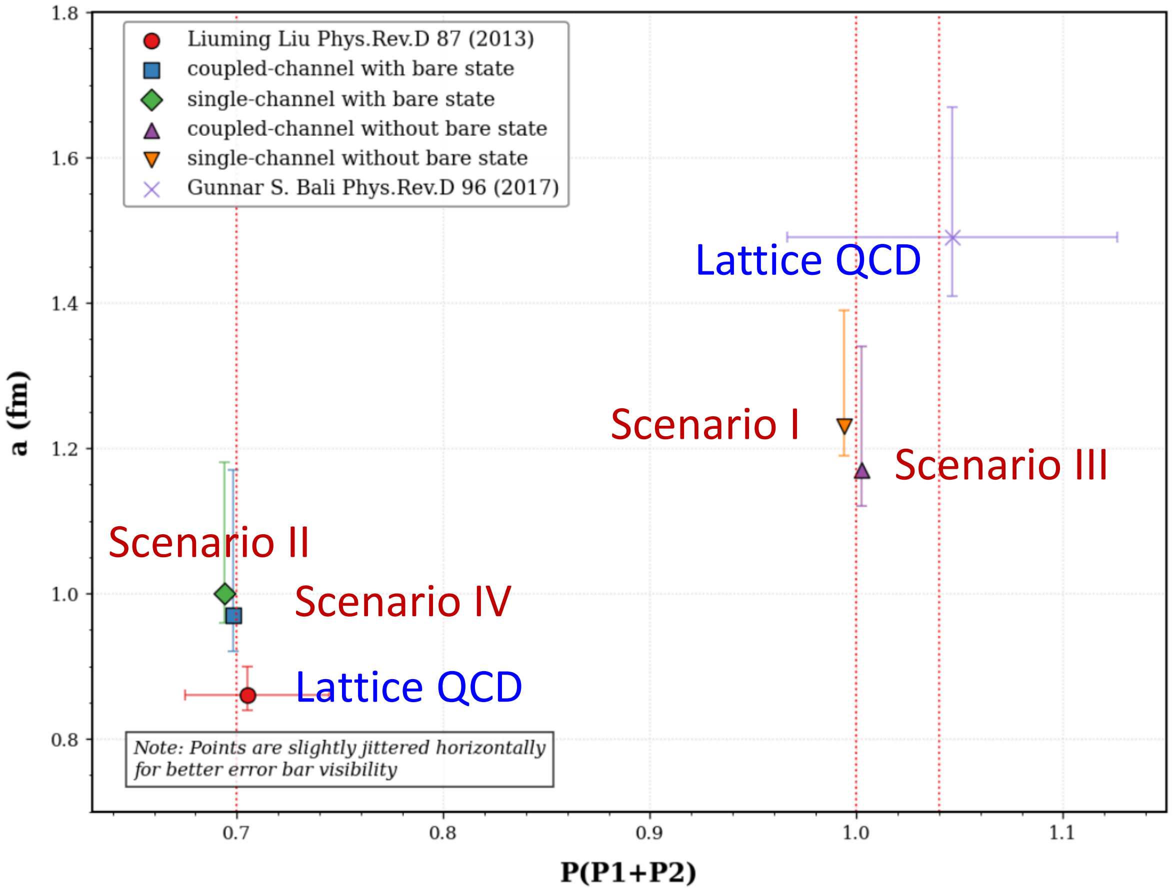
↓ Correlation function

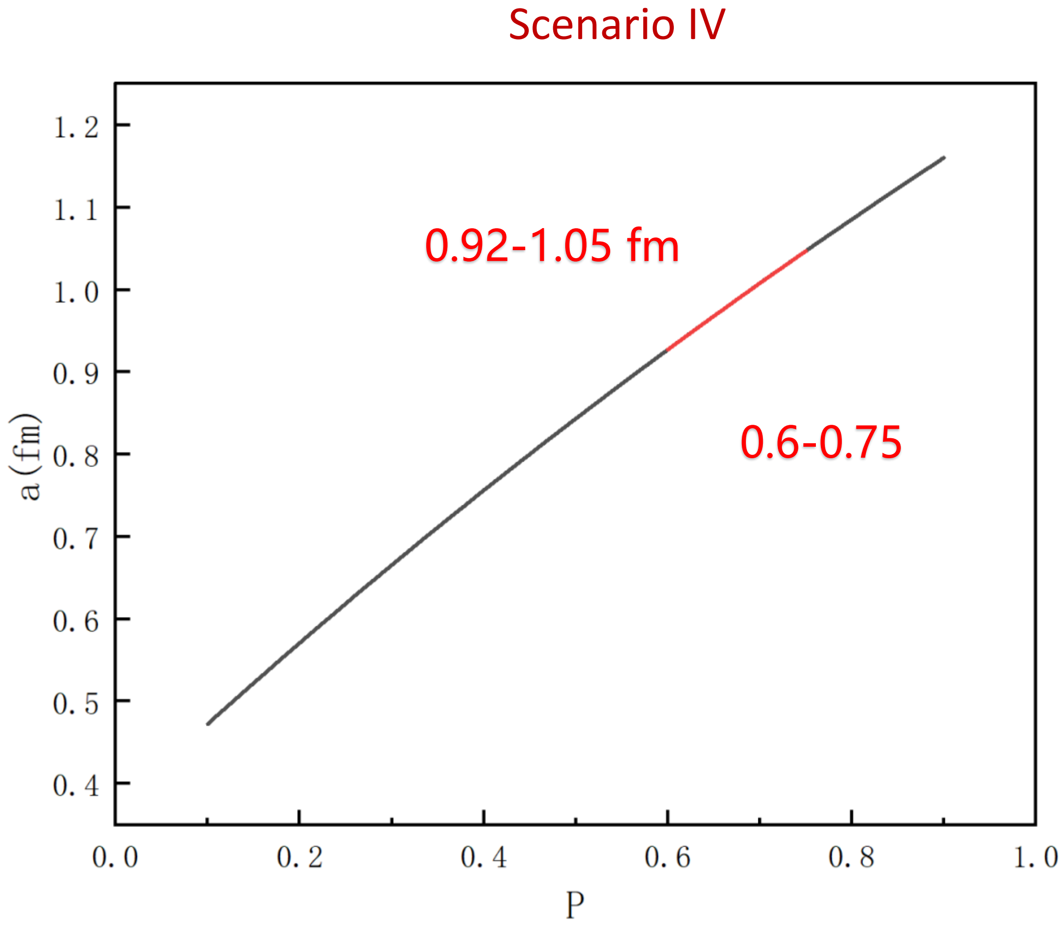
$$C(k) = 1 + \int_0^\infty \mathrm{d}^3 r S_{12}\left[\left|j_0 + T\widetilde{G}\right|^2 - |j_0|^2\right]$$

$$\widetilde{G}(r,\sqrt{s}) = \int_0^{q_{\max}} \frac{\mathrm{d}^3 k'}{(2\pi)^3}\frac{\omega_1+\omega_2}{2\omega_1\omega_2}\frac{j_0(kr)}{s-(\omega_1+\omega_2)^2 + i\varepsilon}$$

$$S_{12}(r) = \mathrm{Exp}\left[-r^2/(4R^2)\right]/(2\sqrt{\pi}R)^3$$

DK Scattering length

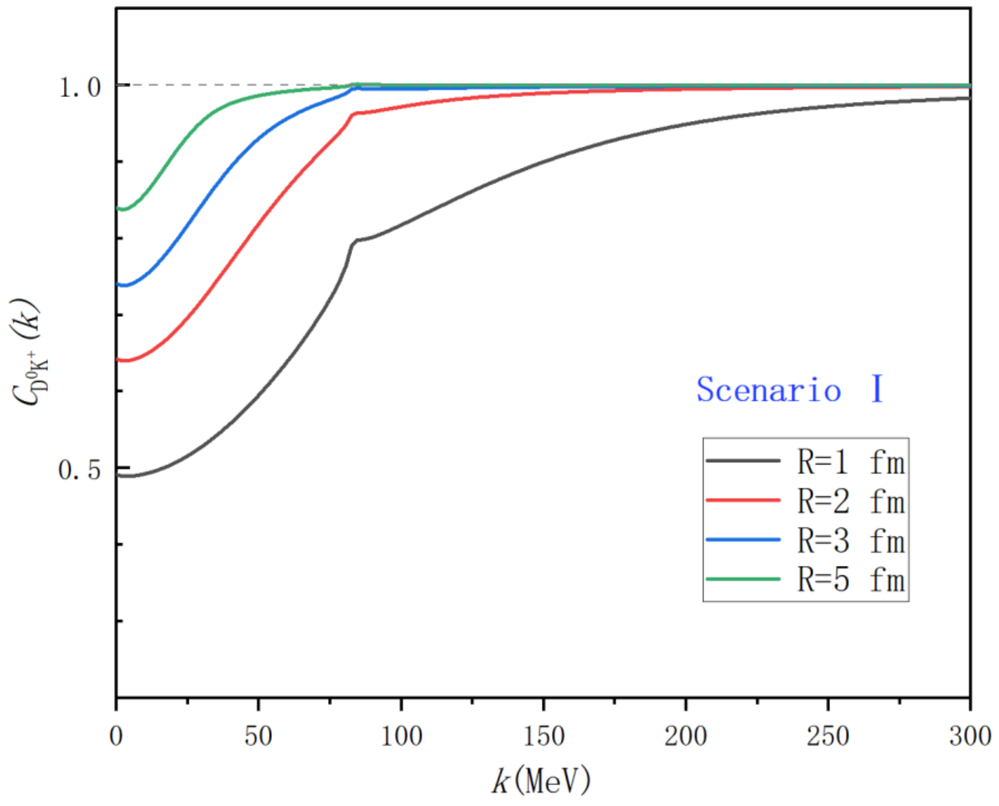


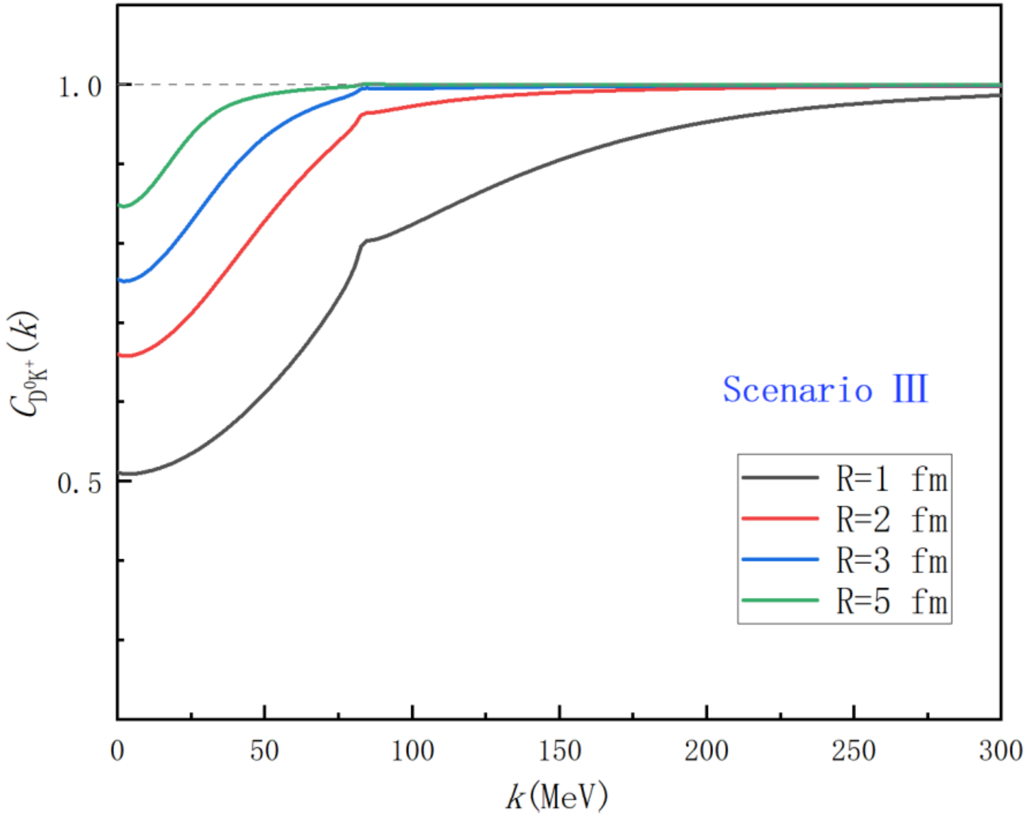


- The coupled-channel effect has a minor impact on the determination of the DK scattering length
- The dressing effect of the bare state leads to an obvious modification of the DK scattering length.

DK Correlation functions

➢ Single channel VS couple channel without the bare state

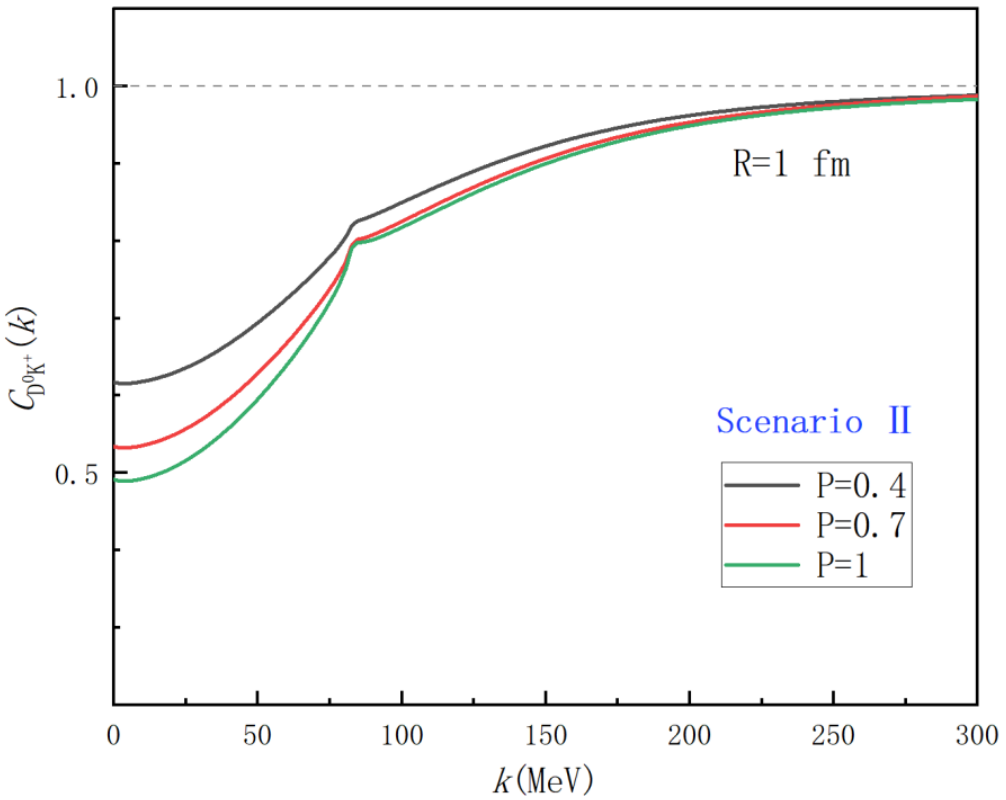


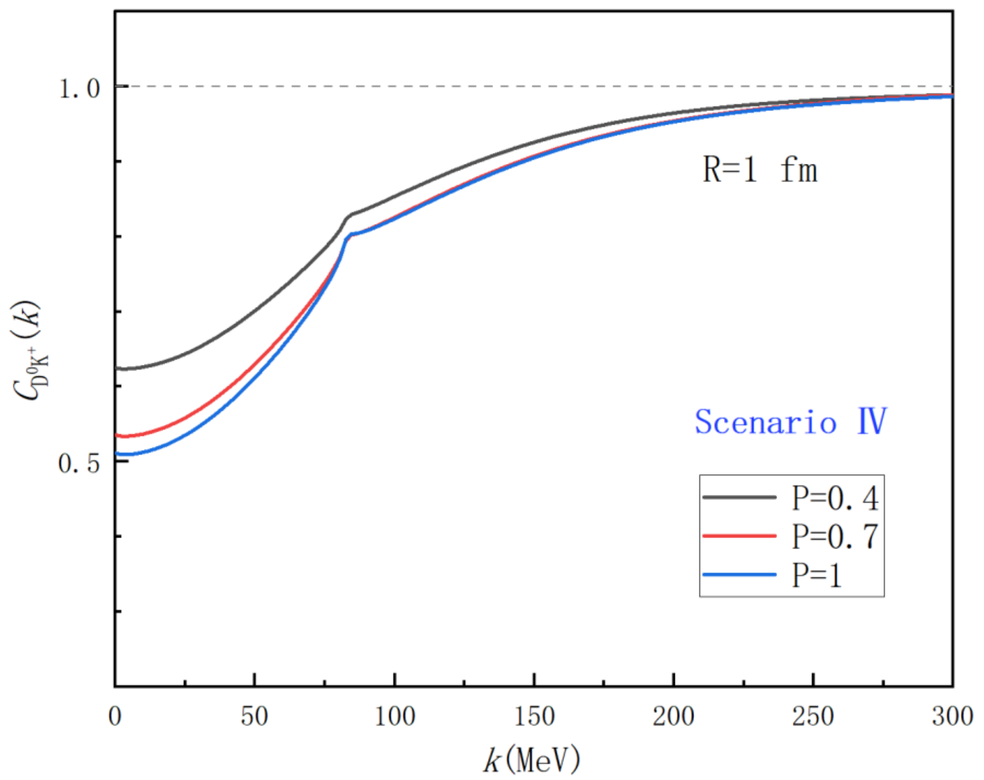


- The coupled-channel effect has a negligible impact on the lineshape of the DK correlation function
- The correlation function exhibits its strongest deviation from unity at R=1 fm

DK Correlation function

➢ **Single channel and couple channel with a bare state**

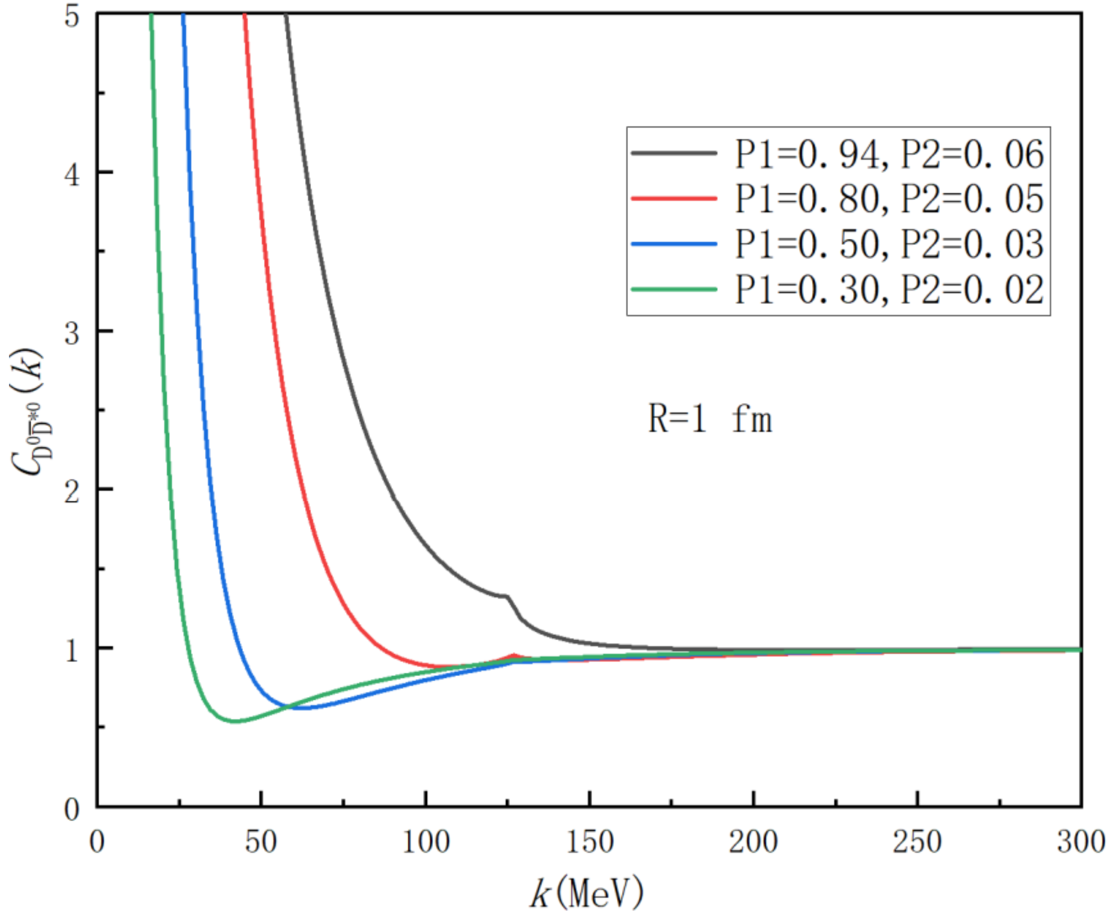




The dressing effect of the bare state modifies the lineshape of the DK correlation function

Correlation function for X(3872)

➢ Couple channel with a bare state



The dressing effect of the bare state significantly modifies the lineshape of the $D^0\bar{D}^{*0}$ correlation function

Outline

- Exotic states and hadron-hadron interactions
- Study the DK interaction in B decays
- Study the DK interaction in heavy-ion collisions
- Summary and Outlook

Summary

- ✓ From the perspective of B decays, the $D_{s0}^{*}(2317)$ cannot be interpreted as a pure hadronic molecule, but rather as a mixture of molecular and bare quark components.

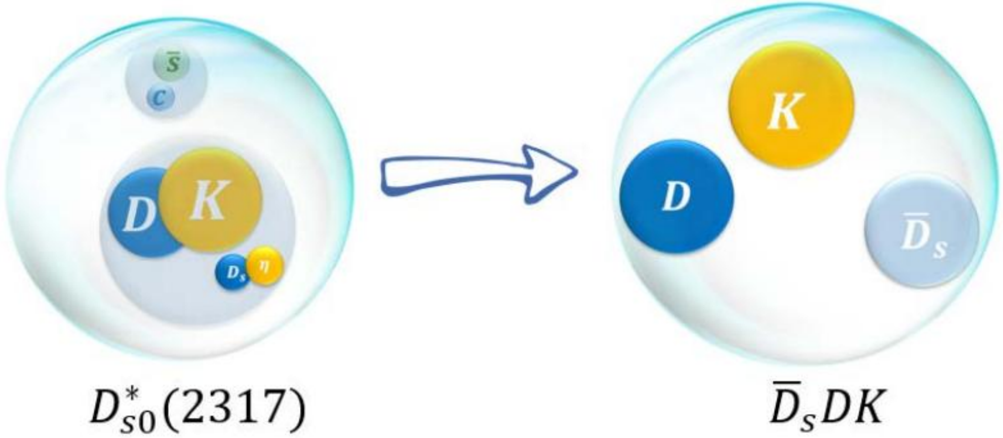
- ✓ Our determination of the DK scattering length through studies of the $D_{s0}^{*}(2317)$ reveals that the presence or absence of a bare component impacts the value of scattering length.

- ✓ By determining the DK potentials from the $D_{s0}^{*}(2317)$ in four scenarios, we predict the DK correlation functions and find that the inclusion or exclusion of a bare component affects their lineshapes, consistent with the studies of scattering length.

Outlook

- With SU(3)-flavor symmetry, we explore the productions of $D\pi$ interactions in B decay and heavy-ion collision via the two-pole structure of the $D_0^*(2300)$

- Utlizing the DK interaction, we can predict the existence of exotic state such as the three-body hadronic molecules. See Tian-Wei Wu's talk

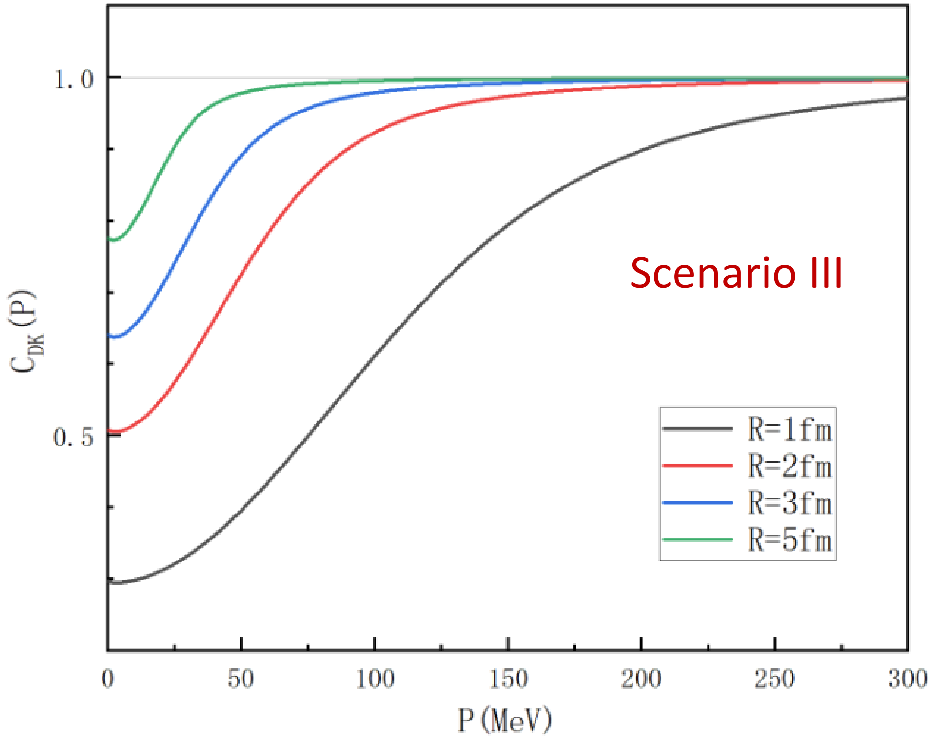


- …….

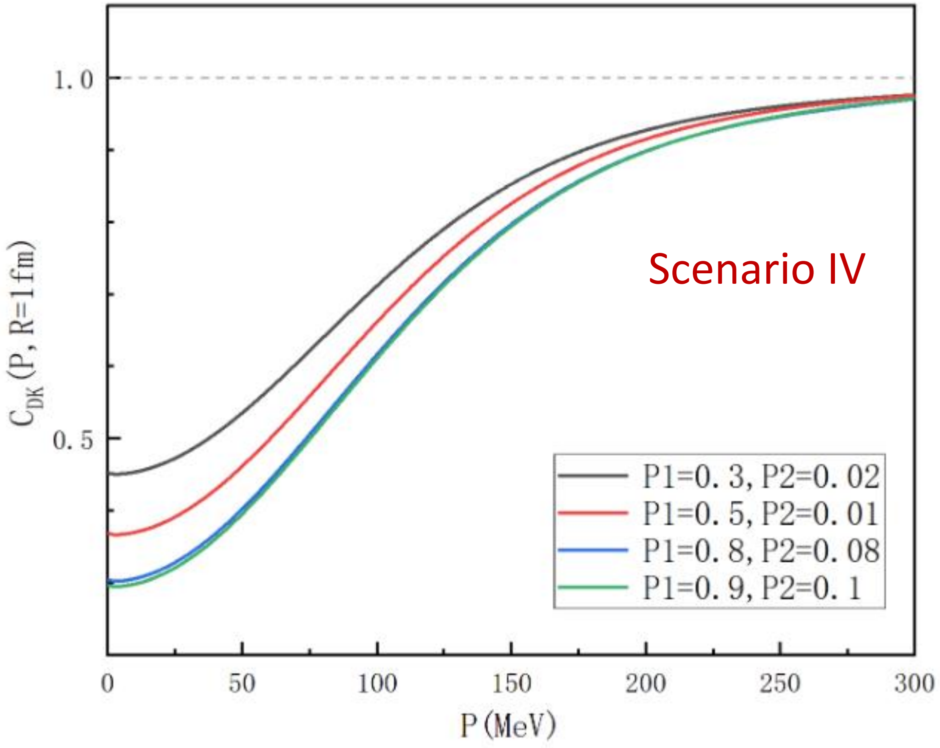
Thanks for your attention!

Correlation function

➢ **Couple channel for with VS without a bare state**



Introducing
a bare state



The dressing effect of the bare state modifies the lineshape of the DK correlation function

Correlation function

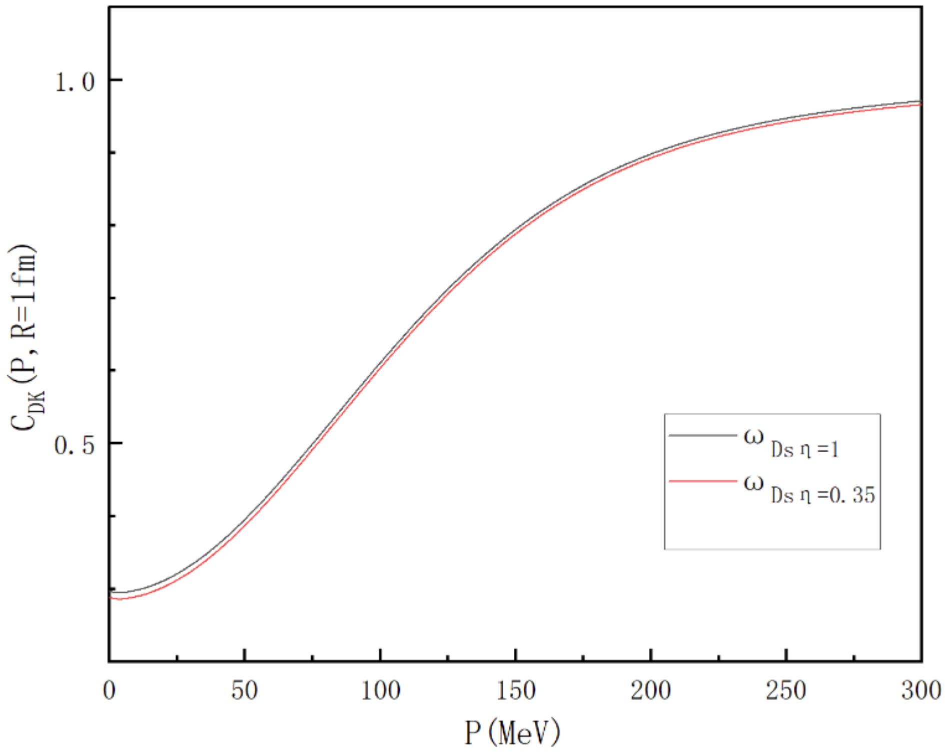
➢ Couple channel affect at source

$$C_{DK}(p) = 1 + 4\pi\theta(q_{\max} - p) \times \int_0^{+\infty} dr r^2 S_{12}(r) \left\{ \left| j_0(pr) + T_{11}(E)\widetilde{G}^{(1)}(r;E) \right|^2 + \left| T_{21}(E)\widetilde{G}^{(2)}(r;E) \right|^2 - j_0^2(pr) \right\}.$$

$$C_j(k_j) = 1 + \int_0^{\infty} d^3 r S_{12} \left[\sum_i \omega_i \left| \delta_{ij} j_0(k_j r) + T_{ij} \widetilde{G}_i \right|^2 - |j_0(k_j r)|^2 \right]$$

$$\frac{\omega_i}{\omega_j} \approx \frac{\exp\left[(-m_{i1} - m_{i2})/T^*\right]}{\exp\left[(-m_{j1} - m_{j2})/T^*\right]}$$

$T^* \approx 154$ MeV



The lineshape of Cfs remains largely insensitive to the weighting of multi-channel effects

Hadron-hadron interactions

- **Experimental data**
- **Lattice QCD simulations**

Constraining → parameters

Effective Field Theory

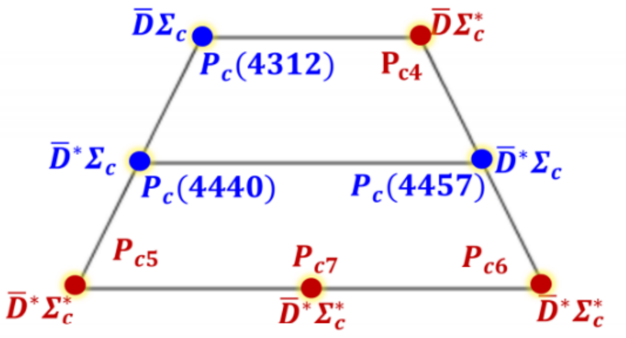
One Boson Exchange(OBE) model

Chiral Unitary Approach(ChUA)

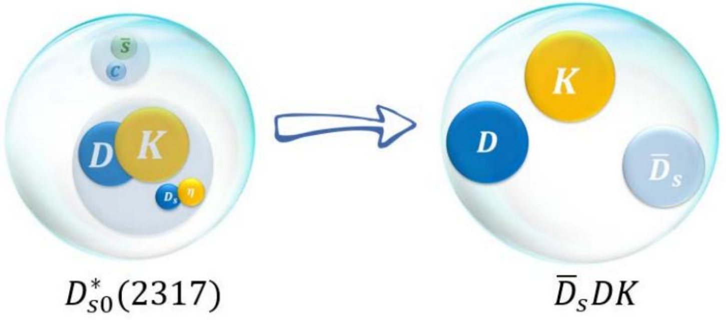
…

➢ Multiplet hadronic molecules

Symmetry
- Heavy quark spin symmetry(HQSS)
- Heavy quark flavor symmetry(HQFS)
- SU(3)-flavor symmetry
- Heavy antiquark diquark symmetry(HADS)



➢ Three-body hadronic molecules



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➢ Momentum correlation functions